

Original Articles

Vulnerability assessment of spring wheat production to climate change in the Inner Mongolia region of China

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ABSTRACT

The main characteristics of global climate change include significant temperature increases and uneven precipitation distributions, which are both limiting factors for the sustainable development of dryland agriculture in semiarid regions. Inner Mongolia, which occupies the largest area of the semiarid region in China, is a good representation of the region's climate and dryland agricultural conditions. Spring wheat is widely grown in this region, but the negative impacts of climate change have seriously threatened spring wheat production in recent years. To adapt to these changes, it is imperative to study the influence of climate change on spring wheat production. We employed a vulnerability assessment method to quantitatively evaluate the impacts of climate change on spring wheat production in Inner Mongolia and recommended specific countermeasures based on the results. The average temperature and precipitation during the spring wheat growing season was 16.5 °C and 224 mm, respectively, from 1961 to 2012. Northeastern Inner Mongolia was characterized by lower temperature and higher precipitation; the eastern region had both higher temperature and precipitation; and the southwestern area had higher temperature and lower precipitation. The climate in this region showed a warming and drying trend from 1961 to 2012, with average temperature during the spring wheat growing season increasing with an average rate 0.3 °C/10a and average precipitation decreasing with an average rate 4.3 mm/10a. Over the study period (from 1996 to 2012), the vulnerability of spring wheat in the eastern, central, and southwestern areas of Inner Mongolia was high, whereas that in the northeast was relatively low. Assuming the adaptive capacity of spring wheat is stable, the comprehensive unit vulnerability of spring wheat production is expected to significantly increase under the investigated climate change scenarios (based on historical climate trends and RCP4.5, RCP8.5 scenarios) relative to average values over the study period. Exposure and regional vulnerability could be reduced by decreasing the proportion of spring wheat grown in vulnerable areas, such as the central and southwestern areas of Inner Mongolia.

1. Introduction

Climate change and its impacts on natural ecology, political economy, and social life have become critical global concerns. Recent studies have shown that “Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850” (IPCC, 2013). In the Northern Hemisphere, the period from 1983 to 2012 was likely the warmest 30-year period over the last 1400 years. Averaged over the Northern Hemisphere's mid-latitude land areas, precipitation has increased since 1901. In other latitudes, the area-averaged, long-term, positive or negative trends in precipitation were

not significant (IPCC, 2013), but uneven distributions of precipitation at regional scales is another major characteristic of climate change.

Semiarid regions account for 13.3% of global land area and contain most of world's dryland agriculture. Agricultural production in semiarid regions contributes to the global food supply and affects social and economic development. Dryland agriculture in semiarid regions of China represents more than 60% of the nation's total arable land (Li, 2004) and is important for national food security. The Inner Mongolia region occupies the largest area of China's semiarid regions, and its climate and dryland agriculture are representative of typical semiarid regions.

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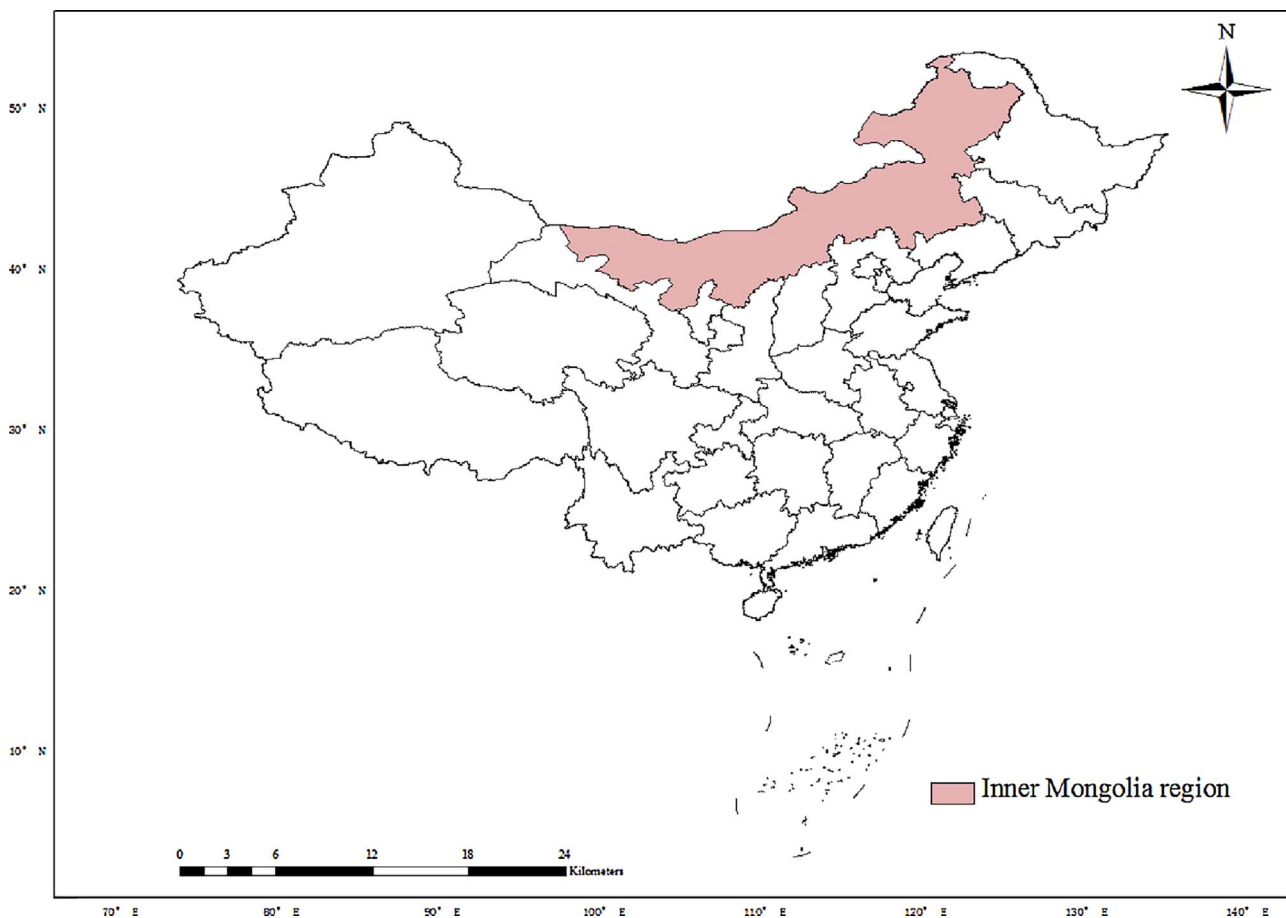


Fig. 1. The study area.

Limited by precipitation and irrigation conditions, dryland agriculture is a risky industry. Natural precipitation, which mainly occurs in summer, is the major available water resource in semiarid regions (Ji et al., 2004). It is often difficult for crops to use moisture due to large soil and water losses. Seventy to eighty percent of precipitation is lost as soil runoff or invalid evaporation, causing frequent drought and decreased grain yield (Li et al., 2014). The actual yield of dryland crops is less than 50% of potential yield (Bu, 2013). Thus, increasing temperatures and uneven precipitation distributions are posing severe threats to dryland crop yield.

Spring wheat, a widely grown dryland crop, is the main food source in semiarid regions, and changes in its yield directly affect food security in these regions. Statistics have shown that the national spring wheat planting area and total yield respectively dropped from 51.9 million hectares and 8.7 million tons in 1980–15.6 million hectares and 6.0 million tons in 2008 (The Ministry of Agriculture of the People's Republic of China, 2009). The climate and daily temperature range in the Inner Mongolia region are suitable for spring wheat growth (Cao et al., 2009). Historically, spring wheat has occupied the largest planting area in this region (Liu et al., 1999), but the area has decreased in recent years (Hou et al., 2009). Decreasing soil water storage and intensifying spring droughts are seriously threatening spring wheat production, and the suitability of planting spring wheat in this region in the face of climate change remains uncertain. Thus, it is urgent for the government to make strategic decisions regarding optimal agricultural management strategies based on the impacts of climate change.

In this study, we evaluated the vulnerability of spring wheat production in Inner Mongolia to climate change. The results provide useful recommendations for countermeasures to cope with the impacts of

climate change.

2. Materials and methods

2.1. The study area

The Inner Mongolia region (Fig. 1) is located in along the northern border of China and the southeastern Mongolian plateau (37°30' to 53°20'N, 97°10' to 126°29'E). It spans a linear distance of 2400 km from east to west and 1700 km from north to south, and most of the area is a plateau. The region has a typical temperate continental monsoon climate with four distinct seasons. Spring is characterized by rapidly increasing temperature and frequent windy weather; summer is torrid and short with concentrated precipitation. In autumn, temperature decreases rapidly, and early frost has a significant impact on agriculture. Winter is long with frequent waves of severely cold weather (Li, 2015).

2.2. Data sources

(1) Historical meteorological data

Meteorological data were acquired from China's meteorological data sharing service network (<http://cdc.cma.gov.cn/home.do>), the Inner Mongolia and WuChuan County meteorological bureaus, etc., and include monthly meteorological parameters from 51 observation sites (Fig. 2) during the spring wheat growing season from April to August 1961–2012 (Dong et al., 2012). Temperature (°C) and precipitation (mm) were investigated because they mostly reflect the characteristics of climate change and strongly impact agricultural production.

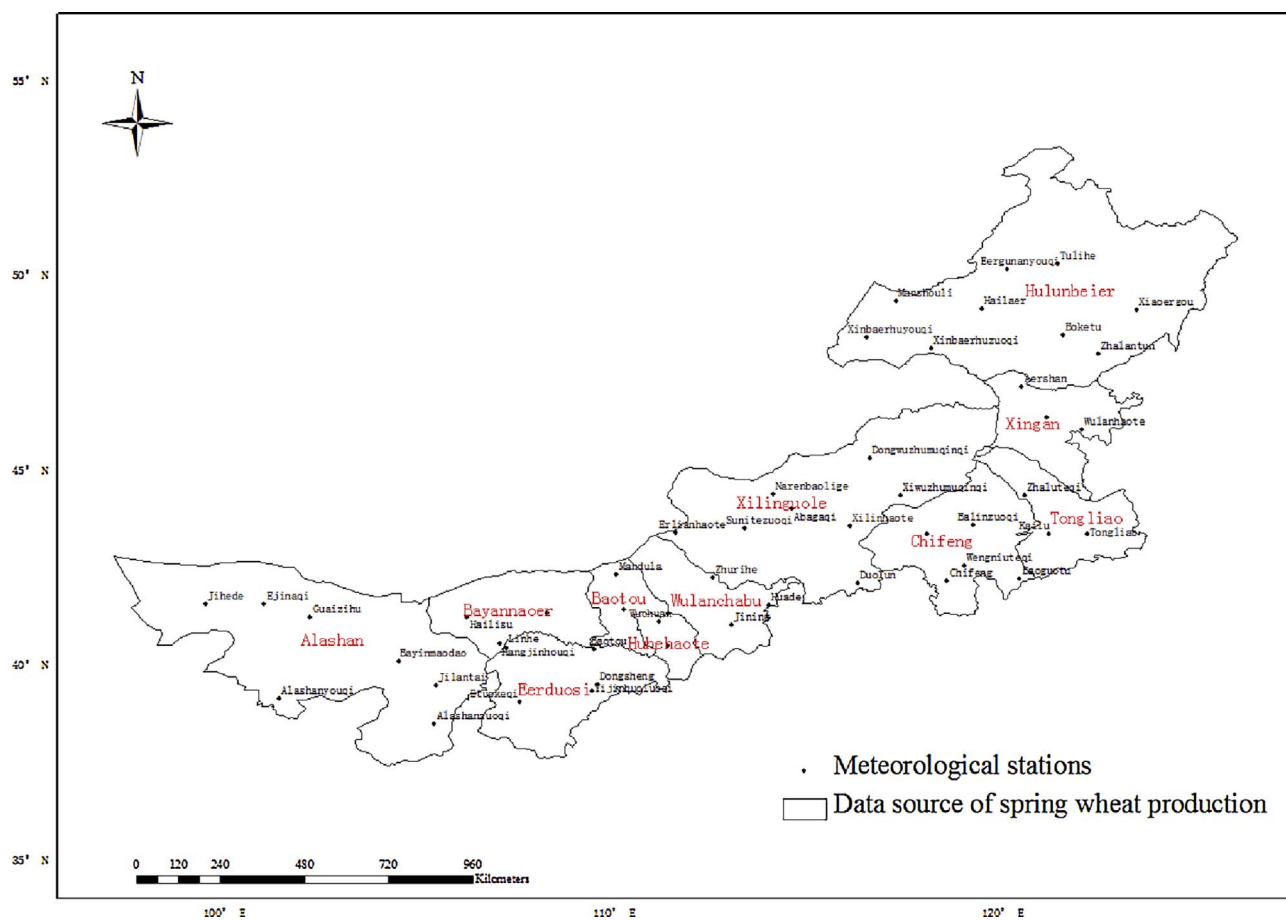


Fig. 2. Locations of meteorological stations and data sources of spring wheat production in Inner Mongolia.

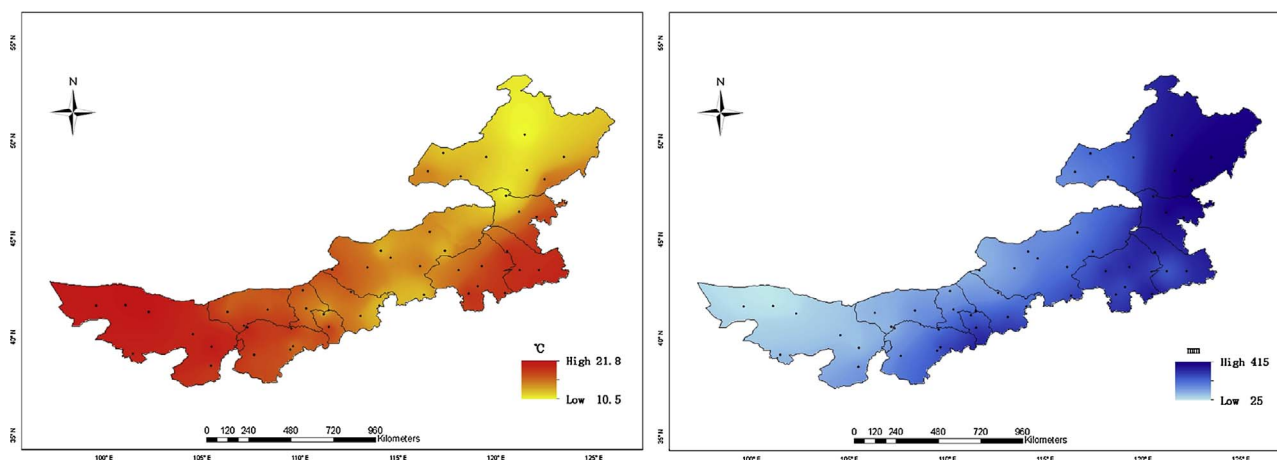


Fig. 3. Spatial distribution of average temperature and precipitation during the spring wheat growing season from 1961 to 2012 in Inner Mongolia (Note: black dots here and in subsequent maps indicate the sites used for spatial data analysis).

(2) Climate scenarios

Climate scenario data were obtained from two sources. First, temperature and precipitation in 2030, 2050, and 2100 were obtained based average rates of change calculated from historical meteorological data. Second, Representative Concentration Pathway scenarios (RCPs) were acquired from the daily data network (<http://cordex-ea.climate.go.kr/main/modelsPage.do>) of the IPCC AR5 for East Asia. The results of two scenarios (RCP4.5 and RCP8.5) were used in this study (Li, 2015).

(3) Planting area, yield, and fertilization level

Planting area, yield, and fertilization level from 1961 to 2012 were acquired from statistical yearbooks including “The fifty years of agro-stockbreeding economy in Inner Mongolia” and “The survey yearbook of economic society in Inner Mongolia”. Data were obtained for 11 cities (Huhehaote, Baotou, Chifeng, Tongliao, Eerduosi, Hulunbeier, Wulanchabu, Bayannaoer, Xingan, Alashan, and Xinlinguole) and 31 counties (Fig. 2).

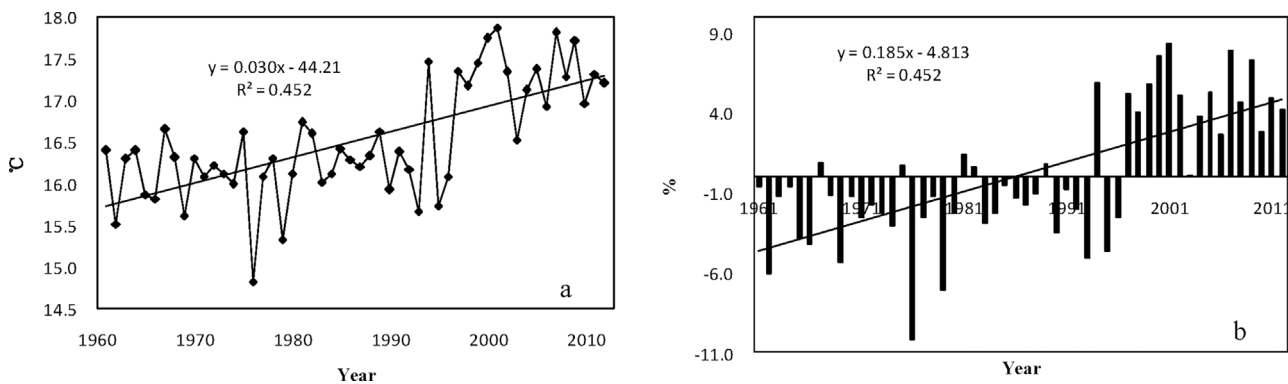


Fig. 4. Temporal variation in average temperature during the spring wheat growing season from 1961 to 2012 in Inner Mongolia.

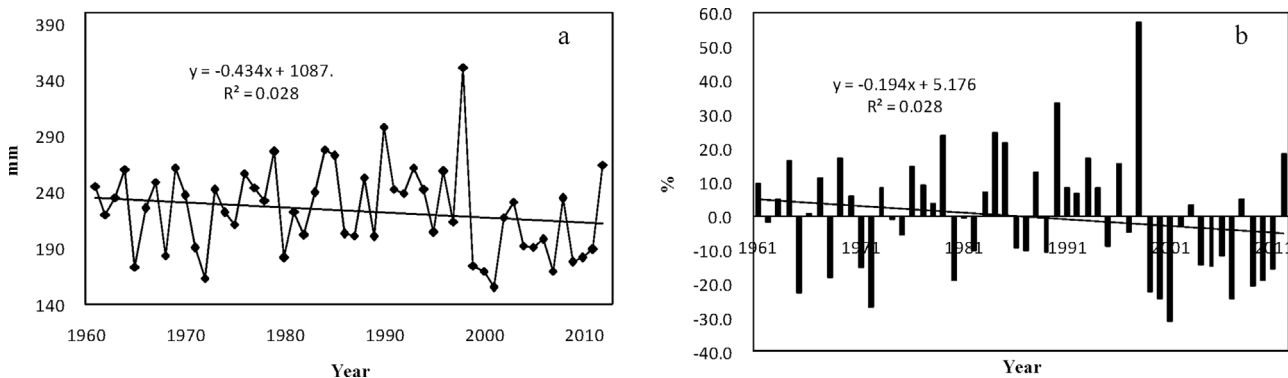


Fig. 5. Temporal variation in precipitation during the spring wheat growing season from 1961 to 2012 in Inner Mongolia.

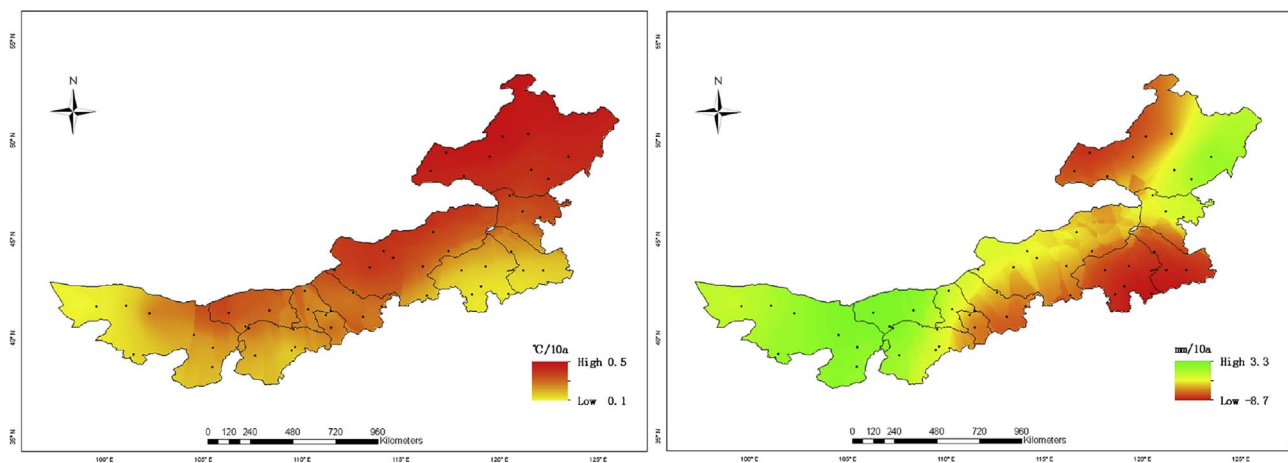


Fig. 6. Spatial variation in average temperature and precipitation during the spring wheat growing season from 1961 to 2012 in Inner Mongolia.

(4) Irrigation level

Irrigation level data were obtained from previously published experiments of water–fertilizer coupling effects (Cui, 2015; Mu, 1999; Yu et al., 2005; Shimshi, 1970) and different irrigation level and yield components (Zhang et al., 2009; Zhang et al., 1999; Ma et al., 2007).

2.3. Methods

(1) Tendency rate

The least squares method was used to describe the trends of temperature and precipitation over time (Lin and Yu, 1990):

$$\hat{x}_t = at + b$$

Where t is time (year), a is the linear regression coefficient, b is the intercept, and the tendency rate is 10 times a .

(2) Regression analysis

Step 1. The least squares method was used to determine the quantitative relationship among variables and estimate unknown parameters.

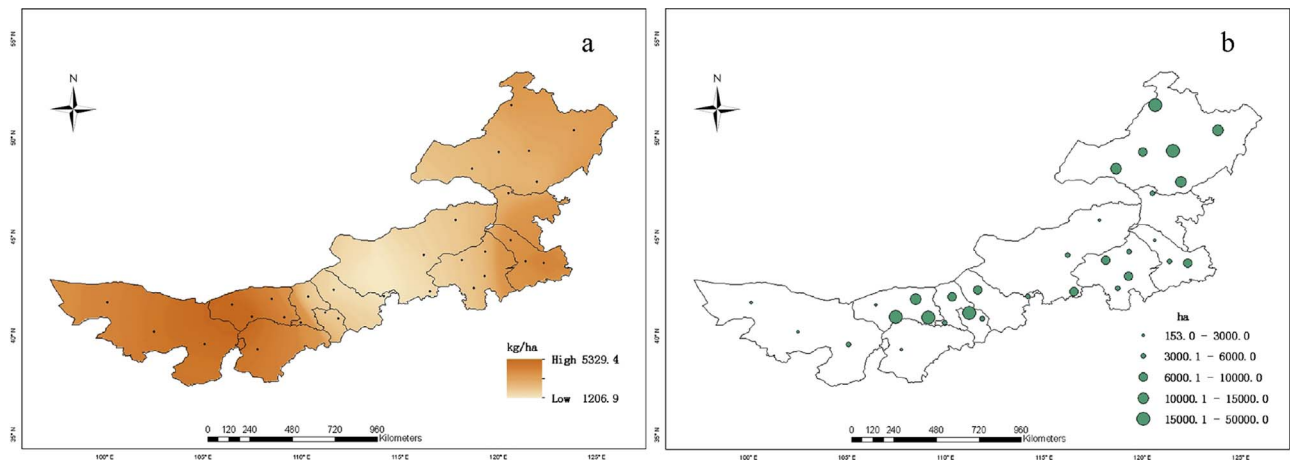


Fig. 7. Spatial distribution of spring wheat unit yield and planting area from 1961 to 2012 in Inner Mongolia.

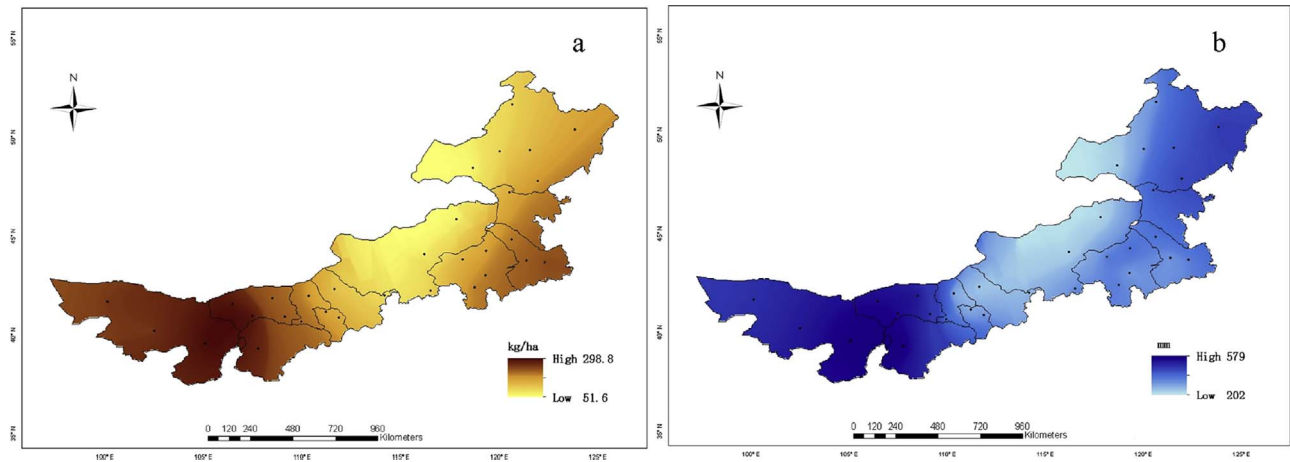


Fig. 8. Spatial distribution of spring wheat fertilization and moisture levels from 1996 to 2012 in Inner Mongolia.

Table 1
Equations for evaluating climatic yield and trend yield.

Evaluating equations		R ²	P
Temperature effects	$Yc_1 = -86.1 x_1^2 + 2681.3x_1 - 20698.1$	0.39	< 0.05
Precipitation effects	$Yc_1 = -0.02x_2^2 + 12.4x_2 - 1836.9$	0.36	< 0.05
Comprehensive effects	$Yc_1 = -84.6x_1^2 + 2687.8x_1 - 0.001x_2^2 + 3.3x_2 - 21922.3$	0.47	< 0.05
Trend yield	$Yt = 14688.8/[1 + EXP(0.00002x_3^2 - 0.004x_3 + 0.000007x_4^2 - 0.008x_4 - 0.000008x_3*x_4 + 4.9)]$	0.90	< 0.01

Note: Yc₁ is climatic yield; Yt is trend yield; x₁ is the average temperature; x₂ is precipitation; x₃ is fertilization level; and x₄ is moisture level.

Step 2. The statistical significance of the models was assessed based on the probability value (P), where P < 0.01 and P < 0.05 indicate extremely significant and significant, respectively.

(3) Separation of climatic yield

Generally, yield can be separated into trend yield, climatic yield, and random error (Dong et al., 2015). Trend yield reflects the yield component due to productivity over a long time period, whereas climatic yield reflects the component affected by climatic fluctuations. The formula is as follows:

$Y = Yt + Yc + e$

Where Y is the overall crop yield (expressed as yield per-unit area,

kg ha⁻¹); Yt (kg ha⁻¹) is the trend yield, which is mainly affected by agricultural technologies; Yc (kg ha⁻¹) is the climatic yield, which represents the influence of climatic fluctuations; and e is the yield component affected by other random factors, which can be ignored (Dong et al., 2015).

Many scholars have proposed methods to separate climatic yield (Fang, 2011; Xie, 1999). Commonly used methods include linear separation (Wei, 1999), sliding average (Jiang et al., 2006; Lian et al., 2007), exponential smoothing (Yin et al., 2000), and logistic functions (Lian, 2005; Hao et al., 2007). Each method has its own advantages and disadvantages. Crop unit yield cannot increase indefinitely; rather, it tends towards a limited quantity that represents the maximum potential yield for a certain region. Therefore, logistical models are more suitable for realistically expressing crop production. The formula is as follows:

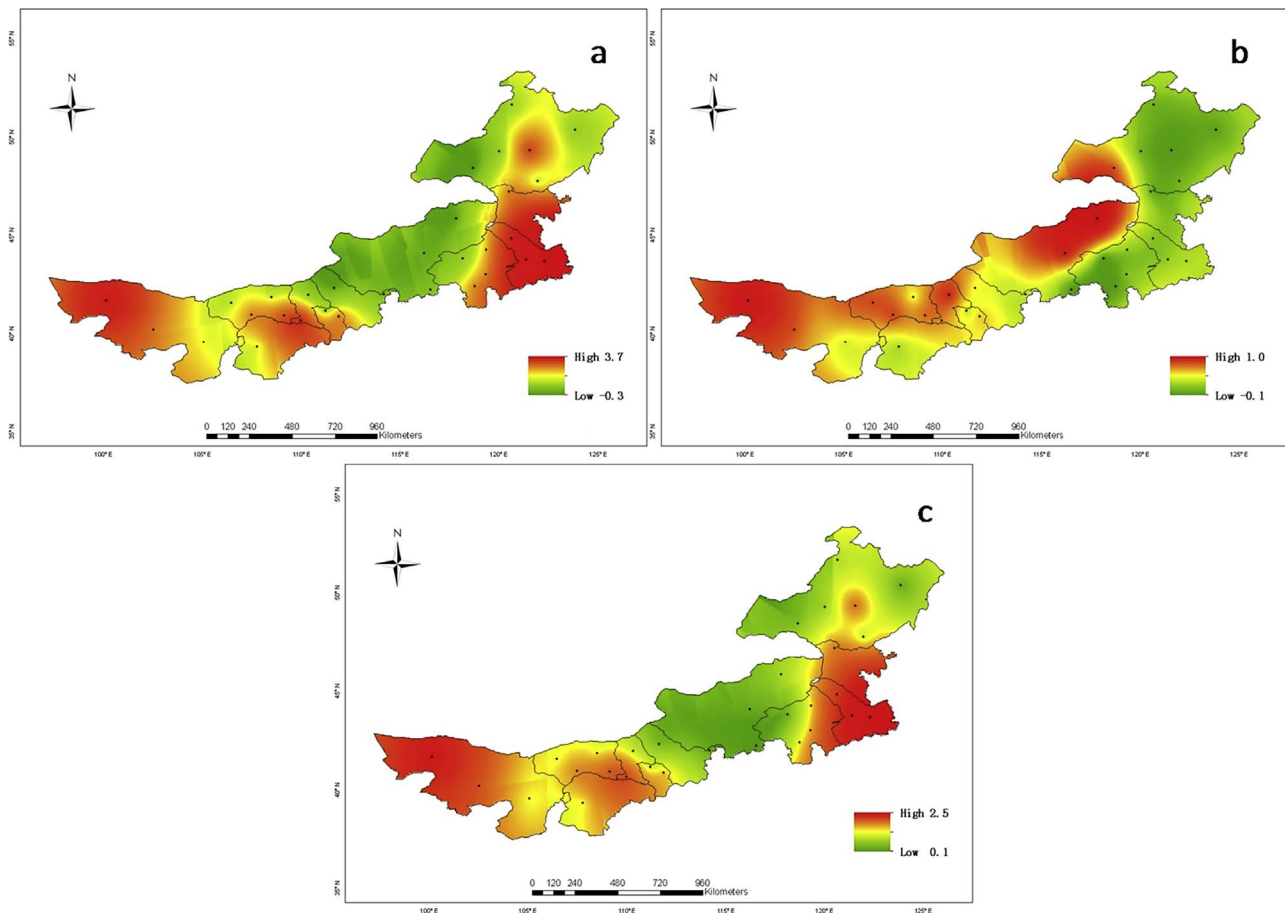


Fig. 9. Spatial distribution of the unit vulnerability of spring wheat production in Inner Mongolia over the study period.

$$Y_t = K / (1 + e^{-bt})$$

Where Y_t is the trend yield, K is the maximum potential yield for a certain region (based on data of potential photosynthetic productivity of spring wheat in Inner Mongolia; Wang, 2015), t is time, and a and b are the regression coefficients. Climatic yield (Y_c) is the difference between crop yield (Y) and trend yield (Y_t).

(4) Vulnerability assessment

The vulnerability assessment method used here has been validated by practical applications including quantitative evaluation, grade division, crop comparison, and planting structure adjustment (Dong et al., 2015; Dong et al., 2016). Based on the conceptual framework of vulnerability in IPCC assessment reports (Eq. (1)), vulnerability (V) is a function of sensitivity (S), adaptive capacity (A), and exposure degree (E) (IPCC, 1995, 2001, 2007, 2014).

$$V = S * E / A \quad (1)$$

Sensitive yield (Y_s , kg ha^{-1}) is used to express the sensitivity of agriculture to climate change (i.e., change in crop yield due to climate change; Dong et al., 2015). Adaptive yield (Y_a , kg ha^{-1}) reflects the adaptive capacity of agriculture, and is calculated as the increase in crop yield due to adaptive measures. Exposure degree is equal to the crop planting area (Dong et al., 2015).

Thus, agricultural vulnerability under climate change can be represented as Eq. (2):

$$V = Y_s * E / Y_a \quad (2)$$

Adaptive yield (Y_a) is correlated with trend yield (Y_t), and sensitive yield (Y_s) is negatively related to climatic yield (Y_c) (Dong et al., 2015). Thus, vulnerability can also be expressed as:

$$V = -Y_c * E / Y_a \quad (3)$$

To separate the effect of exposure level on vulnerability, unit vulnerability and regional vulnerability were defined. Unit vulnerability reflects the change in crop yield per unit area due to climate change (Eq. (4)), and regional vulnerability is the unit vulnerability multiplied by the exposure degree (E) (Eq. (5)) (Dong et al., 2015).

$$\text{Unit } V = Y_s / Y_a \quad (4)$$

$$\text{Regional } V = Y_s * E / Y_a \quad (5)$$

(5) Spatial analysis

ArcGIS10.1 software was used to analyze changes in the spatial-temporal distributions of spring wheat vulnerability. The Kriging method was employed because it considers the effects of extreme values, provides an unbiased estimation, and fully reflects the spatial structure of variables.

3. Results

3.1. Distribution and variation of climatic parameters

The distributions of average temperature and precipitation over Inner Mongolia from 1961 to 2012 are shown in Fig. 3. Over the entire

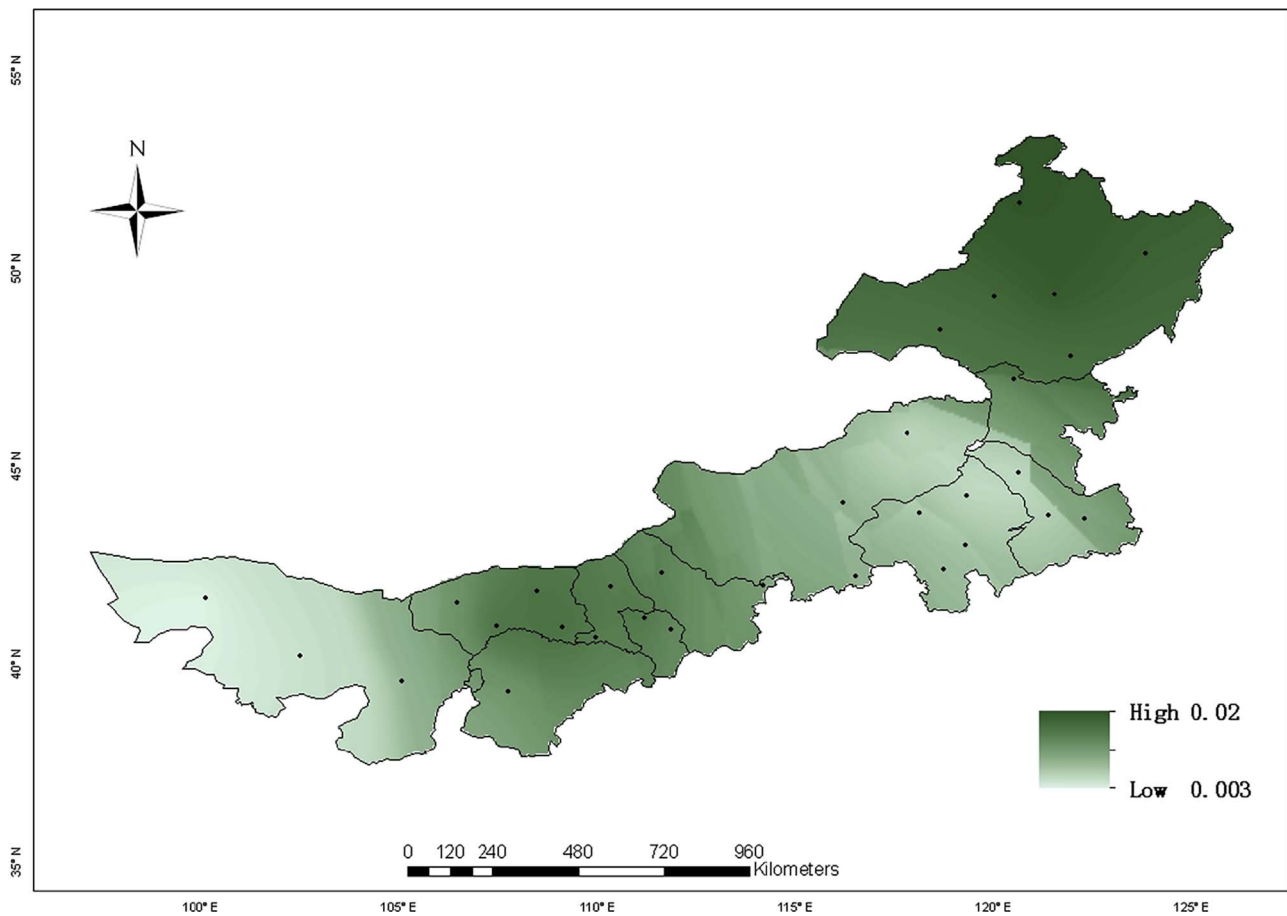


Fig. 10. Spatial distribution of the exposure degree of spring wheat production in Inner Mongolia over the study period.

region, the average temperature and precipitation during the spring wheat growing season was 16.5 °C and 224 mm, respectively. Northwestern Inner Mongolia was characterized by relatively low temperature and high precipitation, the eastern area had both high temperature and precipitation, and the southwestern area had high temperature and low precipitation.

The average temperature across Inner Mongolia increased from 1961 to 2012 with an average rate of 0.3 °C per decade ($p < 0.01$; Fig. 4(a)), which corresponds to an average rate of 1.9% per decade (Fig. 4(b)). The large gap in temperature increase around 1996 is similar with the related researches of IPCC assessment report about the basic and study periods (IPCC, 2013). Thus, 1996 was used as the cut-off point to highlight the impacts of climate change and facilitate global comparisons. The periods from 1961 to 1995 and from 1996 to 2012 represent the basic and study periods in the following assessment, respectively.

The precipitation in Inner Mongolia fluctuated over the study period, but showed an overall decreasing trend with an average rate of 4.3 mm per decade (Fig. 5(a)) or 1.9% per decade (Fig. 5(b)). Overall, the climate over the entire Inner Mongolia region displayed a warming and drying trend, which was even more obvious after 1996.

The central and eastern areas of Inner Mongolia mainly displayed warming and drying trends, whereas the southwestern area showed a warming and wetting trend (Fig. 6). The average rate of temperature increase was greatest in northeastern Inner Mongolia, and relatively smaller in the eastern and southwestern areas. Precipitation showed decreasing trends in the eastern, central, and parts of the northeastern areas. The average decrease in precipitation was greatest in eastern

Inner Mongolia. Precipitation in the southwestern region showed a slight increasing trend.

3.2. Spatial distribution of spring wheat production

The average unit yield of spring wheat in Inner Mongolia from 1961 to 2012 was 1938.5 kg ha⁻¹. The greatest unit yield (5329.4 kg ha⁻¹) was produced in the southwest, whereas the lowest unit yield (1206.9 kg ha⁻¹) was in the central area (Fig. 7(a)). The average planting area was 78185.9 ha. The planting area was greatest in the northeastern area, central area, and eastern southwestern area (Fig. 7(b)).

The average fertilization level in Inner Mongolia from 1996 to 2012 was 157.3 kg ha⁻¹. The southwestern area had the highest fertilization level (298.8 kg ha⁻¹), whereas the central region had the lowest (51.6 kg ha⁻¹; Fig. 8(a)).

The average moisture level, which includes both irrigation and precipitation, during the spring wheat growing season was 338 mm. Moisture level was highest (579 mm) in the southwest and lowest (202 mm) in the central Inner Mongolia (Fig. 8(b)).

3.3. Vulnerability of spring wheat production

As explained above, the periods from 1961 to 1995 and from 1996 to 2012 were set as the basic period and study periods, respectively, and a logistic function was used to separate climatic and trend yield during the basic period (the maximum K value was set as 14688.8 kg ha⁻¹ based on photosynthetic productivity potential).

Equations for evaluating climatic and trend yield were built based

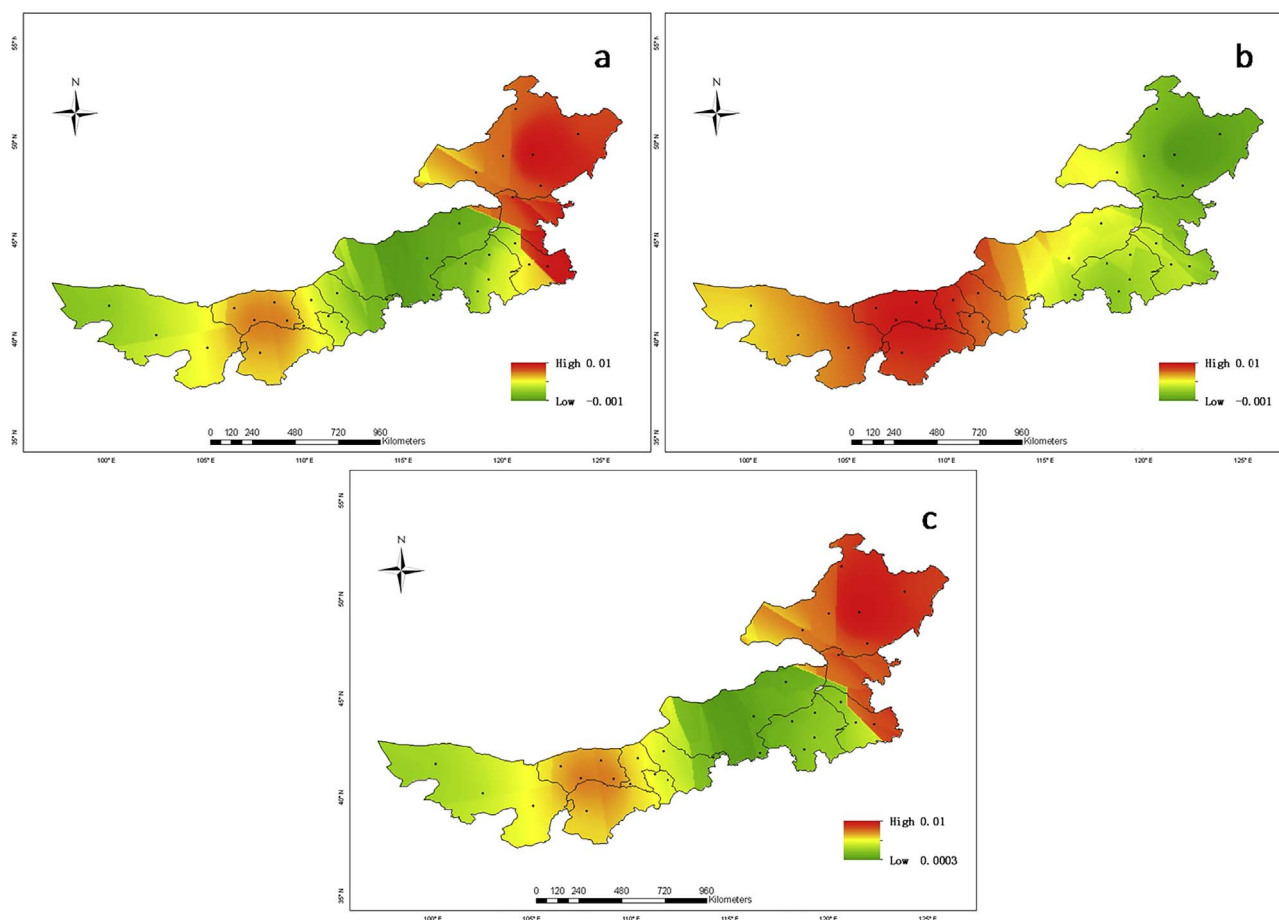


Fig. 11. Spatial distribution of regional vulnerability of spring wheat production over the study period in Inner Mongolia.

Table 2

Future changes in temperature and precipitation based on historical trends in Inner Mongolia.

	Variation in temperature (°C)	Variation in precipitation (mm)
2030	0.6	−9
2050	1.2	−17
2100	2.7	−39

on data from the basic period. Climatic yield was calculated based on temperature, precipitation, and their comprehensive effects, whereas trend yield was evaluated based on fertilization and moisture levels (Table 1).

We calculated sensitive and adaptive yield over the study period by substituting climatic data for 31 counties from 1996 to 2012 into the climatic yield evaluation equations to obtain the simulated climatic yield Y_{c2} (sensitive yield is $-Y_{c2}$). Temperature, precipitation, and combined effects were also calculated. Fertilization and moisture level data were substituted into the trend yield evaluation equations to obtain the adaptive yield, Y_a .

According to Eq. (3), unit vulnerability is the ratio between sensitive yield and adaptive yield. We calculated the unit vulnerability for 31 counties over the study period. The eastern area and parts of central and southwestern Inner Mongolia were more vulnerable to temperature and combined temperature–precipitation effects (Fig. 9). The greatest values of temperature vulnerability and comprehensive vulnerability were 3.7 and 2.5, respectively (Fig. 9(a) and (c)). Precipitation vulnerability increased from northeast to southwest, indicating that central and southwestern

areas are more vulnerable to precipitation effects (Fig. 9(b)).

The exposure degree is the ratio between the spring wheat planting area in 31 counties over the study period and the planting area of the whole region over the basic period. The exposure degree was relatively greater in the northeast, central region, and eastern part of southwestern Inner Mongolia, whereas the exposure degree in the eastern area and western part of southwestern Inner Mongolia was relatively smaller (Fig. 10). A greater exposure degree corresponds to a larger area affected by climate change.

Regional vulnerability is the product of unit vulnerability and exposure degree. The northeastern area and eastern part of the southwestern area were more vulnerable to temperature and combined temperature–precipitation effects (Fig. 11(a) and (c)). The regional vulnerability to precipitation increased from the northeast to southwest (Fig. 11(b)). Adjusting planting structure (e.g., reducing the exposure degree in areas with high unit vulnerability) can help decrease regional vulnerability.

3.4. Vulnerability of spring wheat in future climate scenarios

The effect of climatic changes on spring wheat production was analyzed assuming constant exposure degree and adaptive capacity.

According to historical trends, temperature will increase by 0.6 °C, 1.2 °C, and 2.7 °C in 2030, 2050, and 2100, and precipitation will decrease by 9 mm, 17 mm, and 39 mm, respectively (Table 2).

By substituting data into the vulnerability evaluation equations, future changes in unit vulnerability were determined. The comprehensive unit vulnerability of spring wheat in the study area will increase under predicted climate changes (Fig. 12). The predicted

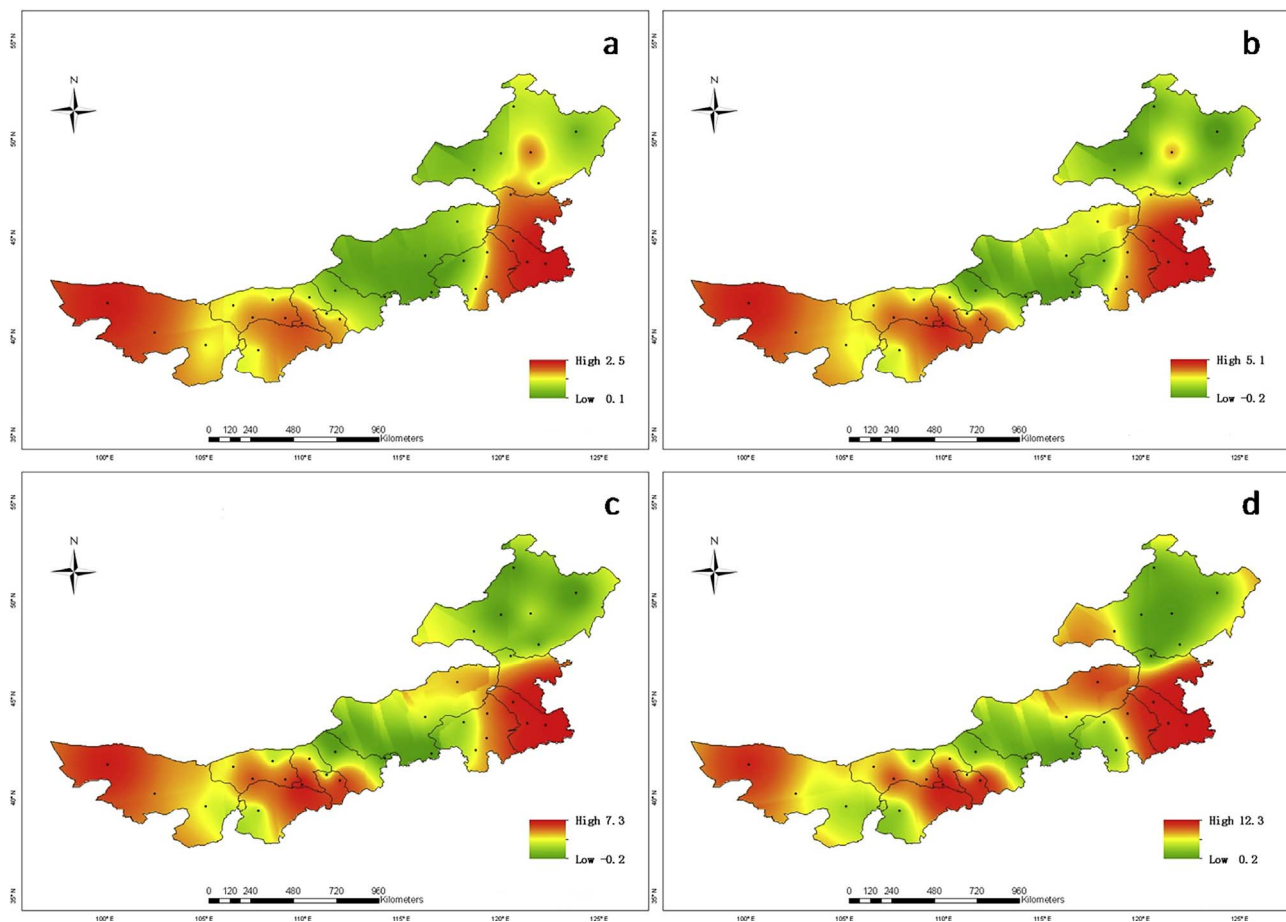


Fig. 12. Spatial distribution of comprehensive unit vulnerability of spring wheat production under future climate change scenarios in Inner Mongolia (Note: a, b, c, and d represent the distribution of comprehensive unit vulnerability during the study period, 2030, 2050, and 2100, respectively; the same applies to subsequent figures).

Table 3
Future changes in temperature and precipitation in Inner Mongolia under RCP4.5.

	Variation in temperature (°C)	Variation in precipitation (mm)
2030	0.7	8
2050	1.3	16
2100	3.0	36

Table 4
Future changes in temperature and precipitation in Inner Mongolia under RCP8.5.

	Variation in temperature (°C)	Variation in precipitation (mm)
2030	1.3	27
2050	2.7	53
2100	6.0	120

changes in temperature and precipitation will increase the vulnerability of the eastern, part of the central, and southwestern areas of Inner Mongolia. In addition, the central area that is vulnerable to combined temperature–precipitation effects will expand.

Under RCP4.5, temperature will increase by 0.7 °C, 1.3 °C, and 3.0 °C in 2030, 2050, and 2100, and precipitation will increase by 8 mm, 16 mm, and 36 mm, respectively (Table 3) (Li, 2015).

Under RCP8.5, temperature will increase by 1.3 °C, 2.7 °C, and 6.0 °C, and precipitation will increase by 27 mm, 53 mm, and 120 mm,

respectively (Table 4) (Li, 2015).

The comprehensive unit vulnerability under RCP4.5 and RCP8.5 shows an overall increasing trend (Figs. 13 and 14). The eastern, part of the central, and southwestern areas of Inner Mongolia will become more vulnerable to combined temperature–precipitation effects. In addition the area that is vulnerable to combined effects will expand.

Based on the above analysis, the comprehensive unit vulnerability of the eastern, part of the central, and southwestern areas of Inner Mongolia was high during the study period and is expected to increase under future scenarios. Due to the large degree of exposure in the central (e.g., Huhehaote and Baotou) and southwestern regions (e.g., Eerduosi and Bayannaoer; Fig. 10), adjusting planting structure is an important adaptive measure in these areas. Reducing spring wheat planting area will decrease the exposure degree, and thus reduce regional vulnerability.

4. Discussion

Objectively and quantitatively quantifying the impacts of climate change on agricultural production is necessary to support effective countermeasures. Many factors, both climatic and anthropogenic, influence the vulnerability of agricultural production. The vulnerability assessment provided in this study evaluated the impacts of temperature and precipitation variations on agricultural production by considering both historical and future climate change. The results can be applied to optimize the use of climate resources and agricultural losses.

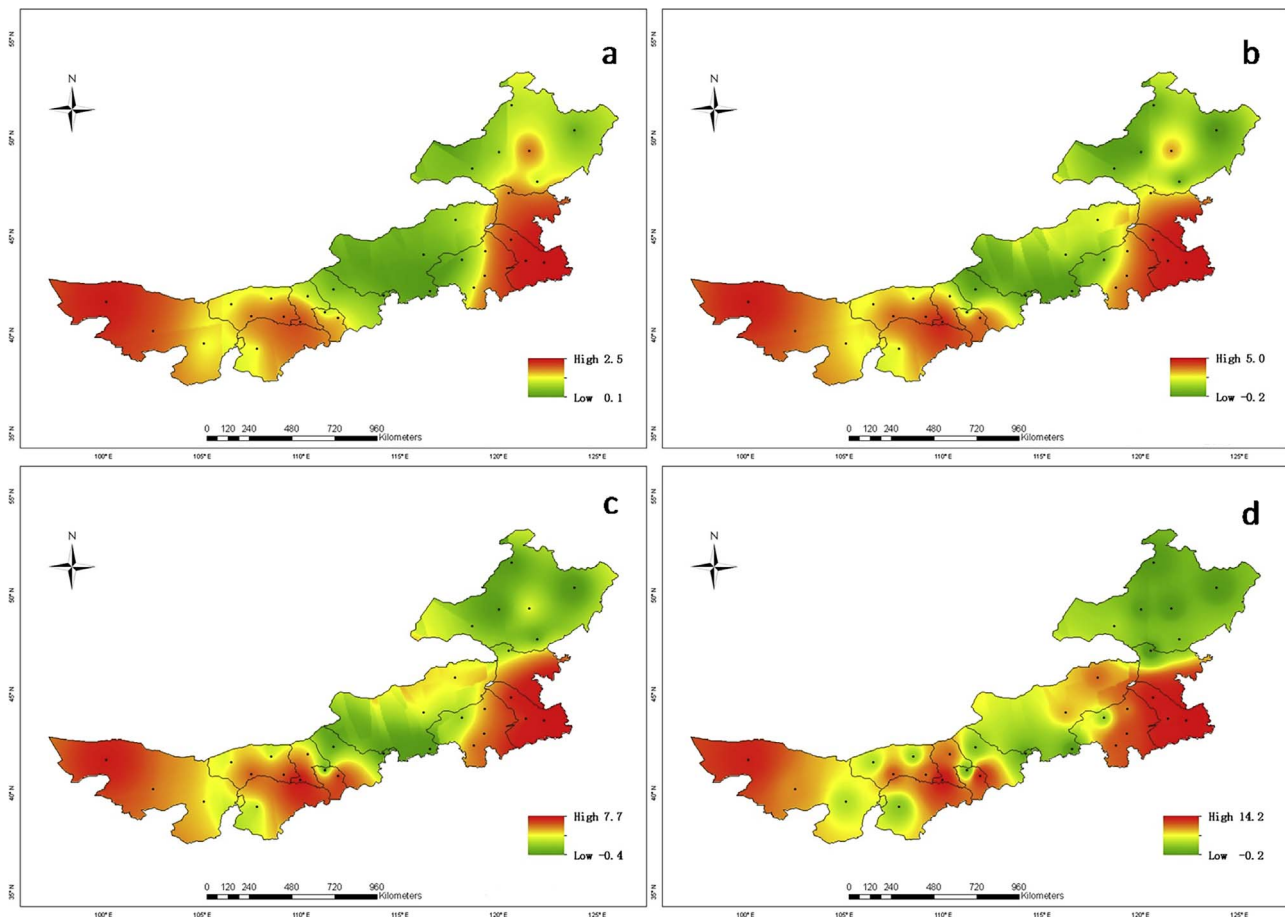


Fig. 13. Spatial distribution of comprehensive unit vulnerability of spring wheat production under RCP4.5 in Inner Mongolia.

The uncertainty of climate change is one of the key difficulties of climate change science. Numerous factors (natural, artificial, dynamic, thermal, etc.) impact the climate, and these factors interact in complex ways. In addition, the mechanisms of climate change are not clearly understood, making future climate predictions difficult. Temperature showed an increasing trend under all three climate scenarios investigated in this study, and the extent of increase was similar between predictions based on historical trends and the RCP4.5 scenario. However, precipitation forecasts showed opposite trends: based on historical trends, precipitation will decrease over the next century, but it is expected to increase under the RCP scenarios. More comparisons among different climate change scenarios are necessary to clarify this uncertainty and prepare relevant measures accordingly.

The complexity of climate change impacts also poses challenges to climate change science. Dryland agricultural production responds differently to changes in various climate factors, and the comprehensive impacts of multiple factors must be considered. The results of this study help to further reveal the complexity of climate change impacts by comparing the independent and comprehensive impacts of various factors.

Future research should focus on the synthesis and optimization of related evaluation indicators. Yield and planting area were used as functional and structural indicators, respectively, to assess vulnerability in this paper. Inclusion of indicators to reflect ecological restoration, environmental pollution, and resource utilization efficiency will increase the effectiveness of vulnerability assessments.

5. Conclusions

The production of spring wheat, the main food source produced in dryland agricultural areas, is suffering from the negative effects of climate change. We evaluated the vulnerability of spring wheat production to climate change based on climate change characteristics in Inner Mongolia, a large semiarid region in China.

From 1961–2012, the average temperature in Inner Mongolia during the spring wheat growing season was 16.5 °C and showed an increasing trend with an average rate of 0.3 °C per decade ($p < 0.01$). The average precipitation was 224 mm and decreased with an average rate of 4.3 mm per decade. Overall, a warming and drying trend was evident over the region.

Spring wheat production in the eastern, central, and southwestern areas of the study region is more vulnerable to changes in temperature and the combined effects of temperature–precipitation changes. The central and southwestern areas are more vulnerable to changes in precipitation. Forecasts based on historical climate change trends show an overall warming and drying trend, whereas forecasts based on RCP scenarios show a warming and wetting trend. Under all investigated scenarios, the comprehensive unit vulnerability of spring wheat production in Inner Mongolia will increase significantly compared with values during the study period, and the range of areas vulnerable to comprehensive effects will expand. Reducing spring wheat planting in areas with high unit vulnerability (e.g., Huhehaote, Baotou, Eerduosi, and Bayannaoer) can help decrease regional vulnerability.

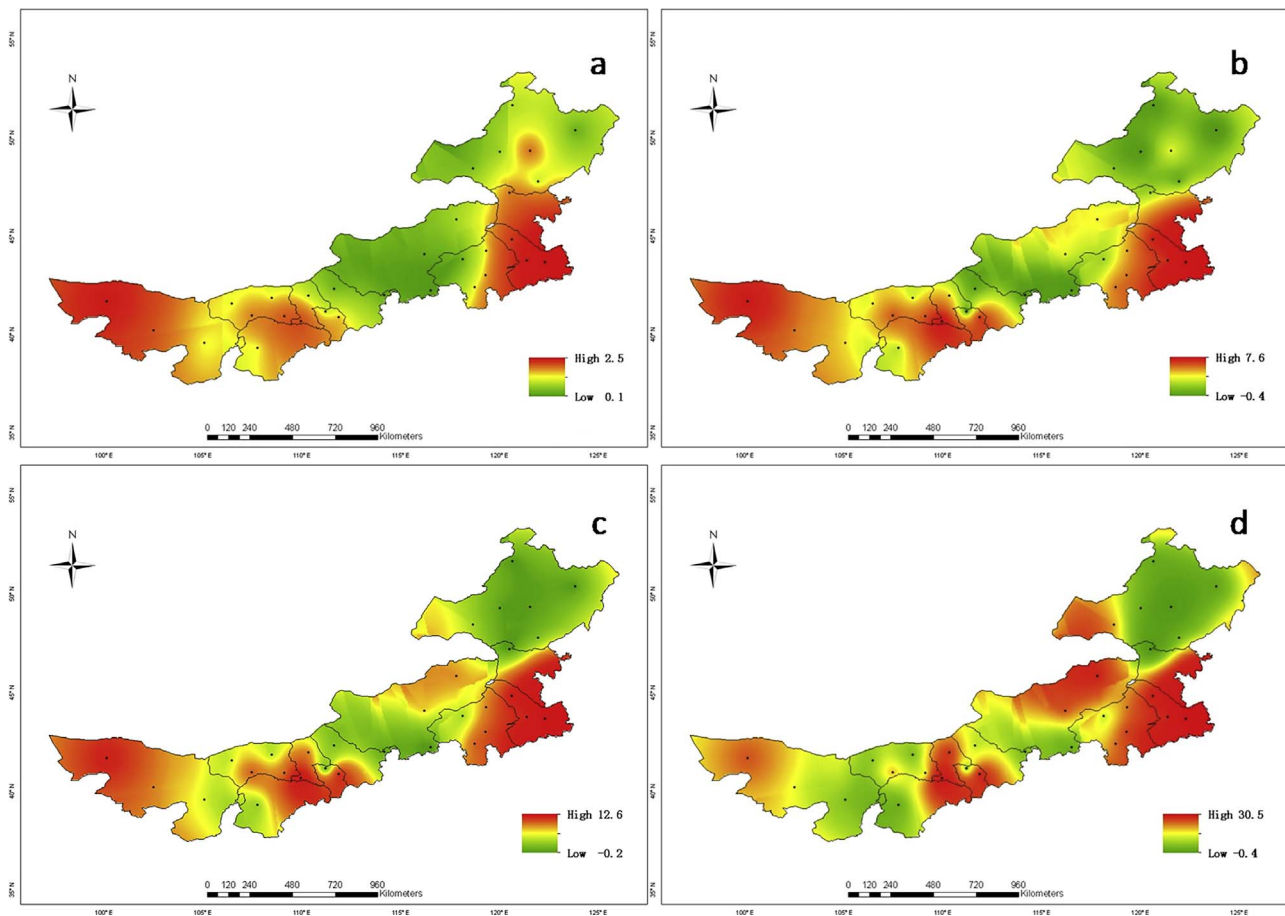


Fig. 14. Spatial distribution of comprehensive unit vulnerability of spring wheat production under RCP8.5 in Inner Mongolia.

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